Simultaneous measurement of temperature and strain using dual long-period fiber gratings with controlled temperature and strain sensitivities

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Abstract: Unambiguous simultaneous measurement of strain and temperature based on dual long-period fiber gratings by controlling their thermal and strain sensitivities is proposed and experimentally demonstrated. The difference in the wavelength peak shift and the separation with the variation of strain and temperature allows discrimination between the strain and temperature effects, respectively.

OCIS codes: (060.2310) Fiber optics and (060.2370) Fiber optic sensors

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1. Introduction

Long-Period Fiber Gratings (LPFGs) have been of interest for applications as band rejection filters and EDFA gain-flattening filters due to their advantages such as low back-reflection and possibility of mass production [1]. LPFG's high sensitivity to external perturbation such as temperature, strain and bending has also led to much interest for sensing applications [2,3]. The liquid level sensor based on the sensitivity of LPFGs to the ambient refractive index was reported in Ref. [4] and application of the peak splitting of LPFGs to bend sensors was reported in Ref. [5]. Recently, simultaneous sensing of multiple perturbations based on LPFGs and fiber Bragg gratings (FBGs) have been developed and reported [6-11]. However, the interrogation of FBGs with LPFGs is difficult since the technique requires the resonant peak of FBGs to be located at the band edge of the resonant peak of LPFGs.

In this work, a simple method for simultaneous measurement of strain and temperature based on LPFGs by controlling the temperature and strain sensitivities is proposed and experimentally demonstrated. Since the LPFGs have higher sensitivity to the external perturbation than FBGs, the sensor performance can be improved significantly compared with the previous reports. The temperature sensitivity of LPFGs was controlled by varying the doping concentrations of GeO_2 and B_2O_3. Two LPFGs with positive and negative temperature sensitivities were fabricated to induce the peak separation with the temperature change. They also had similar strain sensitivity so that resonant peak shift could be obtained with the strain change. Since the temperature sensitivities of two LPFGs are opposite in sign while the strain sensitivities are about the same, the resonant peak separation and shift can occur by the temperature and strain changes, respectively. This allows unambiguous and simultaneous measurement of temperature and strain.

Table 1. Measurement results of the temperature and strain sensitivities of LPFG1 and LPFG2 with the cladding mode order *m*.

	LPFG1			LPFG2		
	$HE_{1,3}$	$HE_{1,4}$	$HE_{1,5}$	$HE_{1,3}$	$HE_{1,4}$	$HE_{1,5}$
Wavelength [nm]	1217.27	1303.13	1488.86	1393.52	1488.86	1681.35
Temperature Sensitivity [nm/ ^{o}C]	0.06	0.07	0.10	-0.57	-0.59	-0.65
Strain Sensitivity [nm/μstrain]	0.41	0.42	0.46	0.43	0.46	0.51

2. Simultaneous measurement of strain and temperature

The temperature sensitivity of LPFGs can be controlled by varying the doping concentration of materials such as GeO_2 and B_2O_3 in the core since GeO_2 has positive temperature sensitivity while B_2O_3 has negative sensitivity [3]. For example, LPFGs will have negative temperature sensitivity if the doping concentration of B_2O_3 is large enough to compensate for that of GeO_2.

We fabricated LPFGs with two kinds of single-mode fibers with different concentrations of GeO_2 and B_2O_3. The fibers used to fabricated LPFGs have the similar properties except the doping concentration of GeO_2 and B_2O_3. The physical parameters of the two fibers are: core diameter = 3.6 μm and 3.8 μm, relative index difference = 1.0 % and 0.8 %, cut off wavelength = 960 nm and 910 nm. The first number is for LPFG1 and the second one is for LPFG2. The cladding diameter is 125 μm for both. For fabrication of the LPFGs, the energy per pulse of the UV laser, grating length and grating period were 1.17 mJ/mm^2, 2 cm, and 400

μm, respectively. The total fluence of the UV laser beam was 7 J/mm^2. The temperature and strain sensitivities of two LPFGs for several cladding mode orders were then measured, and the measurement results are shown in Table 1. LPFG1 and LPFG2 have positive and negative temperature sensitivities, respectively. The data also indicates that the temperature and strain sensitivities of LPFG1 and LPFG2 vary with the cladding mode order.

The strain sensitivity of LPFGs depends on the strain-optic coefficient, grating period Λ, and the cladding mode order [2]. In previous reports, it was shown that the strain sensitivity of LPFG increases with the cladding mode order [2]. The strain sensitivity of the $HE_{1,5}$ mode in LPFG1 was similar to that of the $HE_{1,4}$ mode in LPFG2 and their temperature sensitivities were opposite in sign. This property makes it possible to discriminate between the temperature and strain effects simultaneously.

The simultaneous measurement of strain and temperature with LPFGs is based on control of the temperature and strain sensitivities and induction of the differential peak separation and shift with temperature and strain changes. For two LPFGs with opposite temperature sensitivities, the peak separation is caused by the temperature change when their resonant peaks overlap. The resonant peaks, however, will shift together with the strain change if two LPFGs have the same strain sensitivity.

The temperature and strain changes can be computed from the peak wavelength shifts by using the inverse sensitivity matrix [10]. The measurement resolution will, therefore, depend on the determinant of the sensitivity matrix, and better resolution will be obtained if the temperature sensitivities of the two LPFGs are opposite in sign. The dynamic range of measurement will, however, decrease in this case.

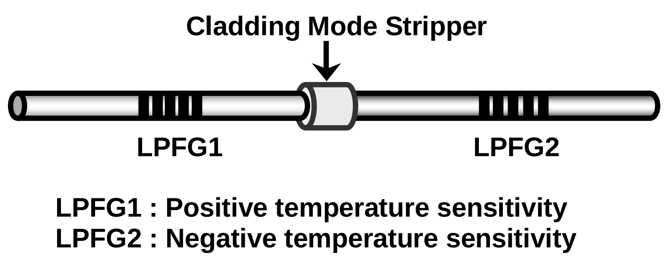

Fig. 1. Schematic of the simultaneous measurement of strain and temperature based on two LPFGs with similar strain sensitivities.

Figure 1 shows the simple structure of dual LPFGs for simultaneous measurement of strain and temperature. Since the cladding modes coupled from the core mode by the first grating can interfere with the core mode again in the second LPFG, it is necessary to remove the cladding modes by inserting a cladding mode stripper between the two gratings. After fabricating LPFG1, we tried to make LPFG2 such that the resonance wavelength coincides with the main resonant wavelength of LPFG1. The total loss including the splicing loss and the loss due to the mode mismatch was less than 0.1 dB. The overall length of the device is about 5 cm. When used as a sensing head, this physical dimension is small enough for civil structures like buildings and bridges.

Figure 2 shows the transmission characteristics of LPFGs with the overlapped resonant wavelength measured by the optical spectrum analyzer (HP 70004A) and the white light source (ANDO AQ-4303B) with the wavelength range wide enough to measure the coupling between the core mode and multiple cladding modes by the LPFGs. The circles show the resonant peaks of LPFG2. In general, the core mode ($HE_{1,1}$) can be coupled to several cladding modes ($HE_{1,m}$) of LPFGs [1] and the multi-resonant peaks appears in the transmission spectrum as seen in Fig. 2 (the dashed line). After fabricating LPFG1, we measured the variation of the transmission spectra of the two gratings during the grating

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formation of LPFG2. The resonant wavelength of LPFG2 shifted to longer wavelength due to increase of the average index during the grating formation and finally overlapped with that of LPFG1 as shown in Fig. 2 (the gray line). The resonant wavelength of $HE_{1,4}$ of LPFG2 overlapped with that of $HE_{1,5}$ of LPFG1, which has similar strain sensitivity and opposite temperature sensitivity. The overlapped wavelength makes it easier to measure the strain and temperature sensitivity with a single light source since we need to detect only one wavelength. All of the resonant peaks of two LPFGs cannot be made to overlap consistently due to different photo-induced refractive index changes with the cladding mode order during the grating formation.

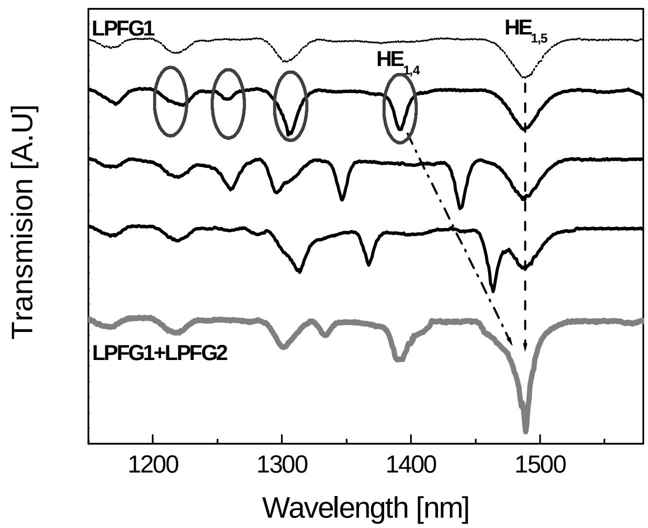

Fig. 2. Evolution of the transmission characteristics of two LPFGs during the grating formation. The dashed and gray lines show the final transmission characteristics of LPFG1 alone and overlapped gratings, respectively. Circles show the transmission characteristics of LPFG2 with UV exposure during the grating formation.

Figure 3 shows the peak separation of LPFGs with variation of temperature and the sensitivity is estimated as 0.69 nm/^{o}C. The transmission characteristics of LPFGs with the temperature change were shown in the inset. The peak separation occurred as the temperature increased due to the opposite temperature sensitivities of the two LPFGs. Since the negative temperature sensitivity of LPFG2 was larger in magnitude than the positive sensitivity of LPFG1, the shift of the resonant peak to the left was larger than to the right.

Figure 4 shows the dependence of LPFGs on the strain change and the transmission characteristics are shown in the inset. Since the two LPFGs have similar strain sensitivity (~0.46 nm/μstrain), the resonant wavelength shifted to the longer wavelength with the strain change. The measured strain sensitivity was 0.46 nm/μstrain. Figure 5 shows the results of simultaneous measurements of strain and temperature. The rms errors of the measured strain and temperature were 8.3 μstrain and 0.7^{o}C, respectively. Consequently, the sensing performance was enhanced by a factor of more than two compared with that of the previous reports [10, 11]. It is believed that the error was caused by the slight slip between fibers and the locking points, resolution of micrometers, the temperature measurement error in the oven, and so on.

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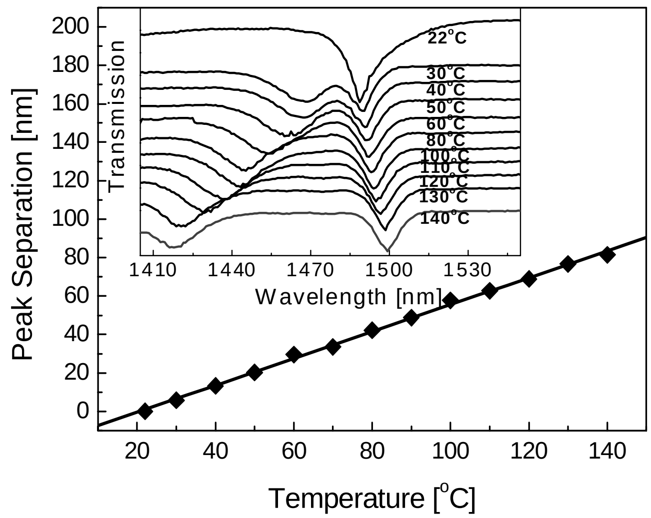

Fig. 3. Measurement results of the peak separation of LPFGs with the temperature change. The sensitivity estimated from the linear fit of the peak separation was 0.69 nm/°C. The transmission characteristics of LPFGs with the temperature change were shown in the inset

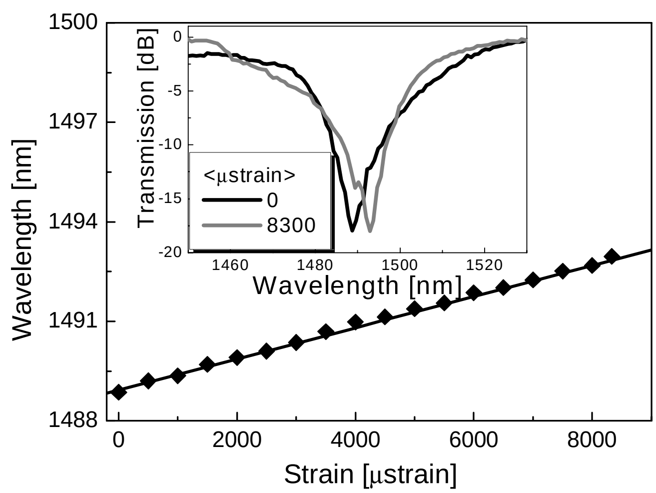

Fig. 4. Measurement results of the peak shift of LPFGs with the strain change. The sensitivity estimated from the linear fit of the peak shift was 0.46 nm/μstrain. The transmission characteristics of LPFGs with the strain change were shown in the inset.

3. Conclusion

In summary, the simultaneous sensing of strain and temperature based the resonant peak shift and separation of LPFGs by the temperature and strain changes was proposed and experimentally demonstrated. The peak separation of LPFGs with the temperature change is attributed to the opposite temperature sensitivities of LPFGs obtained by controlling the doping concentrations of GeO_2 and B_2O_3. The measured sensitivity of the peak separation with the temperature change was 0.69 nm/°C. On the other hand, since the cladding mode

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orders were selected for the two LPFGs such that the strain sensitivity and the resonant wavelength were almost the same, resonant peak shift occurred with the strain change. The measured strain sensitivity of the resonant peak shift was 0.46 nm/μstrain. The rms errors for the simultaneous measurements of strain and temperature were 8.3 μstrain and 0.7^{o}C, respectively.

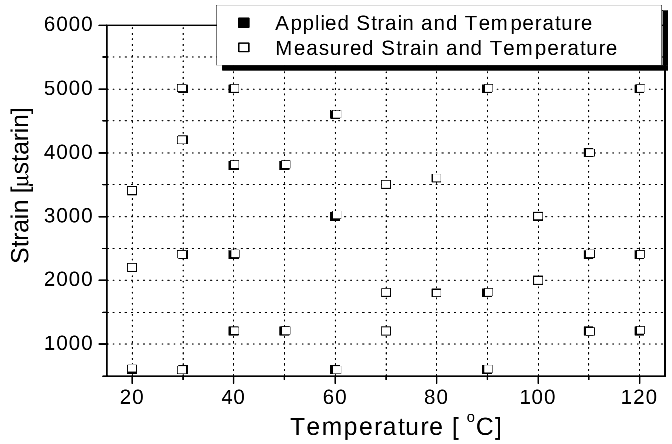

Fig. 5. Results of simultaneous measurement of strain and temperature. The rms error of the measured strain and temperature were 8.3 μstrain and 0.7^{o}C, respectively.

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